Spatially Resolved Residual Stress Characterization Around a Site of Impact Damage

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Problem Statement. The ingestion of debris into aircraft turbine engines, resulting in "Foreign Object Damage" (FOD), leads to the premature catastrophic failure of components subjected to high cycle fatigue loading. To develop methodologies to prevent FOD-related failures in service, the residual stress state left by the impact process must be characterized.

Objective. The objective of this study is to apply the recently developed microdiffraction beamline at the ALS to the characterization of residual stresses associated with simulated FOD damage sites. This work is in conjunction with diffraction studies at SSRL beamline 2-1 with a coarser (300 μm) x-ray spot size.

Approach. While the application of x-ray diffraction techniques to the determination of residual stress fields has been well documented for several decades, the relatively low photon flux of sealed-tube x-ray sources limits the spatial resolution of conventional diffractometers. Because the spatial scale of interest is on the order of 1-500 μm, two spatially-resolved synchrotron techniques have been applied to characterize stresses produced from a projectile impact. A mesoscale technique (spot size ~300 μm) has been used to characterize stresses using traditional polycrystalline methods (i.e. the $\sin^2\psi$ technique). A microscale technique (spot size ~1 μm) has been used to measure residual stresses in individual grains by observing distortion of each grain using Laue micro-diffraction recently developed at the ALS.

Primary Conclusions:

1. Spatial maps of the residual stress state characterized by the diffraction techniques have been compared to numerical analysis performed by Chen and Hutchinson using the finite element method (FEM). There is good agreement between these two results when the impact was formed at moderate velocities (200 m/s), Fig. 1. However, when the impact was formed at high velocities (300 m/s), there is a notable discrepancy between the FEM results and the x-ray results, the latter showing a less-intense residual strain field. These discrepancies are attributed to the quasi-static nature of the first-cut FEM simulation, and subsequent reanalysis, taking into account time-dependent effects, reduces the observed discrepancy.

2. Each impact velocity produces very different levels of residual stress at the surface of the base of the crater. The equibiaxial stresses measured at the base of the crater are approximately -1000 MPa, -500 MPa, and +50 MPa at 0 m/s, 200 m/s, and 300 m/s respectively. Interestingly, in the 300 m/s case which has the highest tensile stresses of the three cases, fatigue cracks do not tend to form at the crater floor, but instead, form at the crater rim due to the formation of incipient microcracks at the rim during the impacting process.

3. The relaxation of residual stresses due to subsequent fatigue cycling ($\sigma_{max,\ nominal}$ = 500 MPa, R = 0.1) after impact has been experimentally observed. This relaxation, however, is only observed when (a) the magnitude of the residual stresses are sufficiently high, and (b) the residual stresses are sufficiently close to the crater to promote stress-amplitude magnification via the stress-concentration factor of the indent. Moreover, there is an indication that more relaxation occurs at the crater floor than at the rim of the crater.

4. There is a high degree of point-to-point variability in the observed residual strain field. A fully annealed sample with no macroscopic residual stresses, can exhibit ~500 με (~50 MPa equivalent uniaxial stress) of variability depending on the location of the spot when interrogated with a 300μm x 300 μm spot size. This observed variablity is well above the resolution of the technique (~100 με or 10 MPa equivalent uniaxial stress). This variability is associated with local residual stresses (so-called "microstresses") locked in during the formation and cool-down of the anisotropic microstructure. An example of a crater survey, Fig. 2, shows the high degree of variability, causing local "hot spots" of strain (the red peaks). The ALS microdiffraction technique verified that the grain-to-grain stress variations are on the order of 50 MPa (500 με) - providing for the first time a direct observation of the origins of these microstresses.

Acknowledgements

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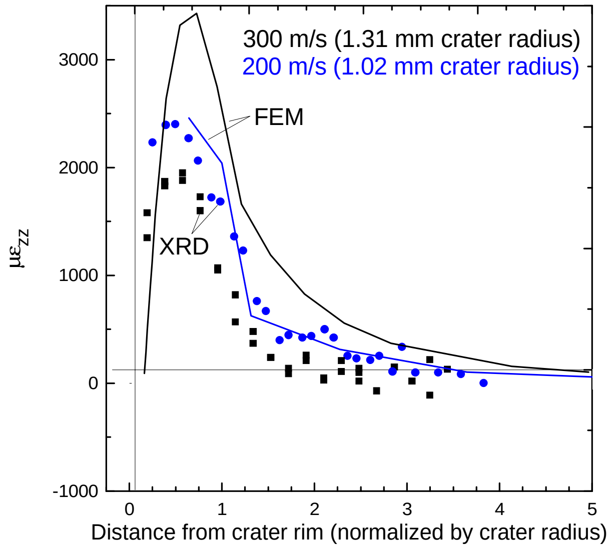

Figure 1. *Survey of residual strain gradient emanating away from the crater rim at the surface of the specimen. The FEM results (lines) compare well to x-ray diffraction experiments (points) at 200 m/s but there is significant discrepancy at 300 m/s*

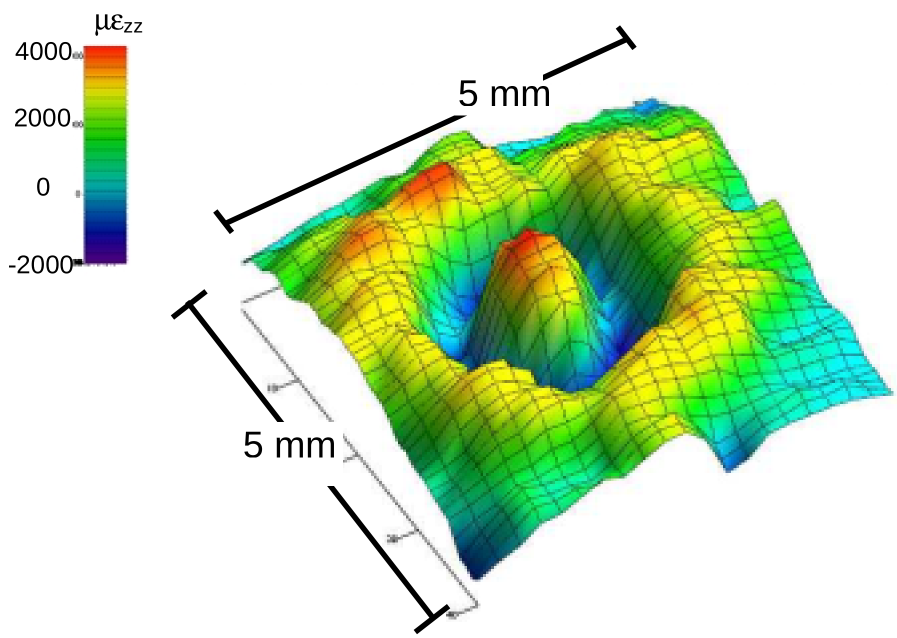

Figure 2. *A surface map of the strain component normal to the surface as measured by x-ray diffraction. Red peaks are associated with high local strain.*